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Aerodynamic Applications of Pressure Sensitive Paint

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A pressure measurement technique based on a photoluminescent coating is being developed and used for aerodynamic applications. Visible light excites probe molecules in the paint and their luminescence is related to the static pressure. Details of the illumination, luminescence detection, and data reduction for this technique are presented. These include key issues such as temperature effects, camera calibration, and model movement. Results from this technique in a variety of flowfields are given. Comparisons with pressures measured using standard wall taps show good agreement.

Nomenclature

b = intercept of the calibration function
I = luminous intensity
K_q = Stern-Volmer constant
M = Mach number
m = slope of the calibration function
P = pressure
P_{O_2} = partial pressure of oxygen
R = fitted slope of the calibration function
S = fitted intercept of the calibration function
T = temperature
λ = wavelength

Subscripts
cal = calibration condition
ex = excitation
ref = reference condition
run = test condition
0 = zero oxygen partial pressure

I. Introduction

SUCCESSFUL development and utilization of pressure sensitive paint (PSP) promises to revolutionize the art of pressure measurement in wind-tunnel testing. Measurements with pressure sensitive paint on wind-tunnel models can potentially provide pressure data with high spatial resolution and data rates that are orders-of-magnitude greater than conventional instrumentation. This technique could be used on model surfaces for flow visualization or to provide detailed aerodynamic and structural loads information. An interdisciplinary team has been formed at McDonnell Douglas to advance this technique. The cooperative effort, including McDonnell Douglas Research Laboratories (MDRL) and the Wind Tunnel Technology Group (Advanced Flight Technologies) of McDonnell Aircraft Company is focused on developing a measurement system for use in wind tunnels.

In addition to determining pressure distributions, pressure sensitive paint has breakthrough potential in early loads prediction for aircraft models. The nearly continuous pressure distribution provided by PSP can be integrated over individual model components (e.g., wings, fuselage, control surfaces, etc.) to provide detailed loads information. Because an aerodynamic force and moment model could be instrumented with paint, building a separate, complicated pressure model could be unnecessary, saving both time and money.

The technique uses a surface coating that contains probe molecules that luminesce when excited by an appropriate light source. Oxygen molecules interfere with this process and decrease ("quench") the amount of luminescence. As a result, the luminescence of the paint varies as a function of the partial pressure of oxygen. Therefore, the intensity of the luminescence can be related to the static pressure of the air at the coated surface. Whereas some paints require ultraviolet illumination, the paint developed at MDRL and used in the work described here luminesces under visible light that is relatively safe and easily manipulated.

II. Fundamentals

This section briefly reviews luminescence and quenching as it pertains to pressure sensitive paint. More detailed discussions of these phenomena can be found in textbooks, as for example, Willard et al.[1] Pressure sensitive paint techniques are based on photoluminescence (which includes both fluorescence and phosphorescence). A probe molecule is promoted to an excited electronic state by absorbing a photon of appropriate energy. Photoluminescence is a mechanism by which the molecule can lose the excess energy by emitting a photon and return to the ground electronic state. During this process lower energy photons are emitted, i.e., the emitted light is red shifted compared to the excitation light. Fluorescence is the emission of light generally within a time on the order of 10^{-8} s and arises from a singlet-singlet transition. In contrast, phosphorescence is a delayed emission generally within a time on the order of 10^{-3}–100 s and arises from a triplet-singlet transition. Figure 1 shows a schematic of the lowest energy level transitions. An alternate transition to the ground state is provided by a collision with an oxygen molecule. Rather than emitting a photon, the excess energy of the probe molecule is absorbed by the oxygen during a collisional deactivation. This process is called dynamic quenching. As the number of oxygen molecules increases in a given volume, the frequency of collisional deactivations increases, which lowers the luminescence. The luminescence of a molecule when exposed to oxygen can be modeled (in many cases) by the Stern-Volmer relation

$$I_0/I = 1 + K_q P_{O_2} \tag{1}$$

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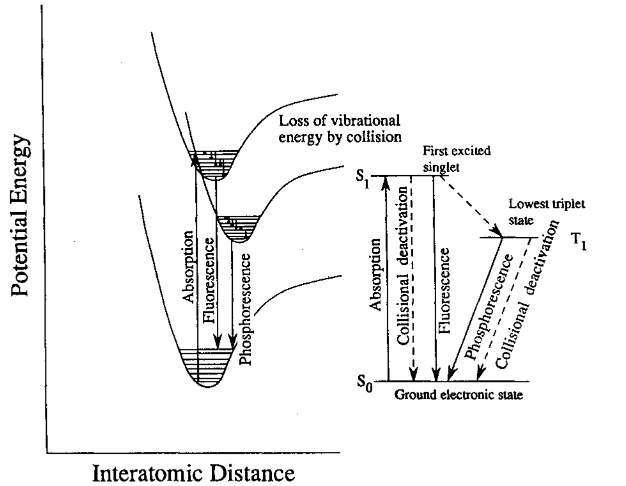

Fig. 1 Schematic of the energy transitions for a photoluminescent probe molecule.

where I is the luminescence, I_0 the luminescence in the absence of oxygen, P_{O_2} the partial pressure of oxygen, and K_q is the Stern-Volmer constant. Both I_0 and K_q are functions of temperature.

Some of the difficulties in using pressure sensitive paint can be recognized by more closely examining Eq. (1). The behavior of the luminous intensity with pressure for several values of the Stern-Volmer constant are shown in Fig. 2. The luminescence decreases with increasing pressure. A larger K_q is desirable, because it represents a higher measurement sensitivity at any given pressure. However, a large K_q could be a disadvantage at higher pressures because the reduced emission intensity may result in unacceptably low signal-to-noise ratios. In other words, as pressure increases, a given change in the luminescence (e.g., one grey level) corresponds to a larger increase in the pressure and the pressure resolution decreases. Subsonic wind tunnels frequently operate near atmospheric pressure and the pressure changes are usually small, making these measurements particularly difficult.

In the simplest paint formulation, the paint is a single layer of a binder compound containing probe molecules. The binder must be permeable to oxygen. More complex versions of the paint include combinations of an adhesive layer, a variety of binders, and additives that modify the permeability of the paint to oxygen.

III. Background

Photoluminescence and quenching by oxygen have been under study for several decades. Utilizing this phenomena as a tool for flow visualization was first proposed in 1980 by Peterson and Fitzgerald.[2] They described a technique in which a surface was coated with a fluorescent dye that was excited by blue light. Either oxygen or nitrogen was injected through a wall static pressure tap. A streak of bright luminescence was observed on the wall in the direction of the surface flow when nitrogen was introduced, due to reduced quenching. A dark streak was observed due to an increase in quenching caused by injecting oxygen. Unfortunately, the sensitivity of the dye to oxygen quenching was relatively low and the oxygen permeability of the binder was low. The paint layer was also rough, relatively thick, and did not adhere well.

Since the Peterson and Fitzgerald work, both computer and image processing hardware have been developed to a level where the concept of oxygen quenching can be extended to the quantitative measurement of pressure. Scientific-grade charge-coupled device (CCD) detectors can provide up to 16 bits of resolution with a 2000 × 2000 pixel array for measuring luminescence. Personal computers can quickly reduce and store the large quantities of data that are generated by such cameras. Image processors can analyze and display the paint response at video rates providing real-time visualization of surface pressure distribution. Using these developments, several investigators have extended the work of Peterson and Fitzgerald to use luminescence to quantify the measurement of pressure.

Kavandi et al.[3] have reported a technique in which phosphorescence was used to measure static pressure distributions on the surface of an airfoil at Mach numbers from 0.30 to 0.66. They used a paint with platinum octaethylporphyrin as the probe molecule, and they used ultraviolet illumination ($\lambda = 380$ nm). A low-light video camera recorded the response of the coating and was digitized to 8-bit resolution. One hundred video frames were averaged and in that average image five adjoining rows of pixels were averaged to determine the luminescence. Static pressure taps on the airfoil surface were used to perform in situ calibration of the paint resulting in a quoted measurement accuracy of 1%. In general, good agreement was shown between pressures measured using the paint and those measured using conventional transducers. Poor agreement was shown near the leading edge where the surface curvature was high. Concern was also expressed about the temperature sensitivity of the paint and photodegradation.

Gouterman et al.[4] quantified the effects of photobleaching of the coating used in Ref. 3 for two wavelengths. The ratio, I_0/I, was reduced by approximately 45% when illuminated for 1 h at $\lambda = 380$ nm and by 40% at $\lambda = 540$ nm in the same time (illumination intensity was equal to that used for making pressure measurements). They also showed that by increasing the paint thickness from 5 to 17 μm, I_0 increased by 50%.

Similar efforts have been reported by Vollan and Alati[5] in developing a commercially available system. An assessment of the system was reported by Engler et al.[6] Using a cropped delta wing at Mach numbers from 0.5 to 0.85, both temperature and luminescence were measured and used to determine the pressure distribution. Temperature was measured using both infrared cameras and thermocouples and the luminescence was detected using a "high sensitivity" CCD camera. Pressure tap measurements were made both with and without the paint layer on the wing surface. The paint layer caused approximately a 3% change in the pressure measurements, which was attributed to either added thickness or craters forming around the pressure taps. Similar to the results of Kavandi et al., good agreement was shown between the paint measurements and the transducer measurements on the flat portions of the wing. However, "large" disagreement between the pressure taps and the paint response was noted on areas of the wing with large, and even mild curvature, which they concluded was caused by "changed" reflections in those regions.

The aforementioned results demonstrate the promise and viability of this measurement technique. Clearly, the development is in its early stages. Refinement of paint mixtures, optimization of illumination and detection systems, improved procedures for calibration, temperature compensation, compensation for model movement, and multiple camera systems will enhance measurement capabilities.

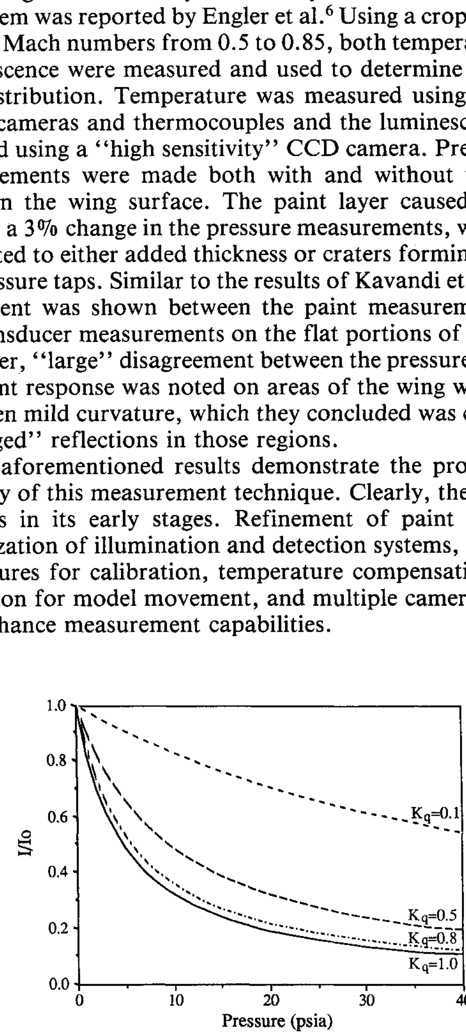

Fig. 2 Photoluminescence as described by the Stern-Volmer model for a range of sensitivities.

The paint used in the present work was designed for high sensitivity to pressure, low sensitivity to temperature, and excitation under visible light. The specific formulation of the paint is considered McDonnell Douglas proprietary information and will not be discussed. The paint was sprayed onto the model surface using standard spray painting equipment which produced a reasonably uniform and repeatable coating. Applications of the paint in a variety of flowfields provide valuable learning experiences for refining the technique. In addition, the problem of relative movement between the model and the camera is discussed and a preliminary solution is implemented.

IV. Instrumentation

Proper selection, matching, and calibration of components is the most important (and difficult) aspect of constructing a system. An accurate pressure measurement system based on pressure sensitive paint results from the refinement of several highly integrated subsystems. These include an illumination system, a detection system, and a data processing system. The first two subsystems must be customized to satisfy the requirements of the paint, such as the proper illumination wavelength and proper filters on the cameras. In addition, these two systems are strongly dependent on the particular application and the pressure range to be measured (which effects the amount of light available for detection). The data processing system must be capable of collecting, storing, and reducing large amounts of data quickly. A sketch of one PSP system configuration used in this investigation is shown in Fig. 3.

The paint was illuminated with an argon laser that was tuned to supply blue light at $\lambda = 488$ nm. The illumination levels were kept low to eliminate the effects of photobleaching on the paint response (no significant change in the paint's response/calibration was measured over the duration of these experiments). Fiber optics were used to overcome wind-tunnel access problems. An optical fiber connected to a trifurcated bundle distributed light over the model surface. Care was taken to separate the illuminating light from the luminescence in frequency to avoid an artificial offset in the data. Because the laser generates distinct wavelengths of light sufficiently far from the luminescent wavelength, segregation using color filters was a relatively simple task.

The type of detector used to sample the paint response is dependent on the required results. If good spatial resolution of surface pressure distribution is required, alternatives include still photography, low-light video cameras, or the scientific-grade CCD array of a digital camera. None of these alternatives provide good frequency response (standard video rates would resolve frequencies up to 15 Hz). The image rate for the digital camera in this work was one frame in 4 s. If high-frequency response is required, alternatives include a high-speed movie camera or photodiode. A combination of detector types has proven to provide good wind-tunnel information.

The results reported subsequently were sampled using three types of detectors: a photodiode, a low-light CCD video camera, and a Photometrics digital camera (model no. MXX200L) with a scientific-grade, cooled CCD array. For all cases, the light entering the detectors was filtered to block all of the illuminating light. The photodiode was used in a proof-of-concept experiment where the response of the paint in a pressure vessel was focused on the photodiode using a simple lens. Early tests were conducted using a relatively inexpensive low-light video camera (0.5 lux) with a standard NTSC composite video output. Later work was done using the Photometrics 14-bit digital camera having 512×512 pixel resolution, extremely low-light detection capabilities, and very good resolution of the luminous intensity.

Several options were available for processing data. Standard video output from the low-light camera was either recorded directly or viewed in real-time through an 8-bit image processor. Although the digitizer has 8 bits of resolution, the actual resolution of the luminous intensity has been shown to be approximately 6–7 bits, due primarily to the bandwidth of the composite video signal. The CCD array and electronics of standard video cameras are not precision scientific instrumentation. However, standard video cameras can provide reasonable spatial resolution, and the poor signal-to-noise ratios and limited low-light capabilities can be addressed with averaging techniques. A Macintosh IIx was used to control the digital camera and acquire the data from the camera. The data were then transferred to a Vax mainframe for the determination of pressures. The results from these manipulations were displayed on a Silicon Graphics work station.

V. Data Reduction

To apply the Stern-Volmer model, the luminescence I over the surface of interest and the luminescence in the absence of oxygen I_0 are required. An alternative is to determine the luminescence at two different pressure conditions. In many cases, purging the oxygen in the vicinity of the painted surface can be impractical. Thus, using a ratio of images taken at two pressure conditions allows the determination of pressures and eliminates the need for I_0

In the work described here, the two images were a "flow on" (run) case where the pressures were unknown, and a "flow off" (reference) image in which the pressure distribution was constant on the surface and equal to atmospheric pressure. When using a linear model as in Eq. (1), normalizing the intensity by that which corresponds to a pressure near the pressure of interest is optimum, thus minimizing errors associated with assuming linear behavior. The pressure and intensity at this point are referred to as P_{cal} and I_{cal}, respectively. Using this normalization of a linear model, the two cases are

$$\frac{I_{cal}(T_{ref})}{I_{ref}} = m_{ref}P_{ref} + b_{ref} \tag{2}$$

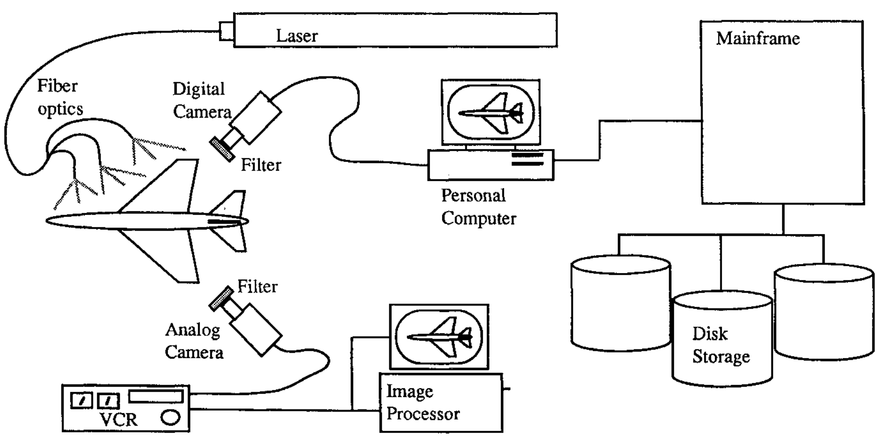

Fig. 3 Schematic of measurement system based on pressure sensitive paint.

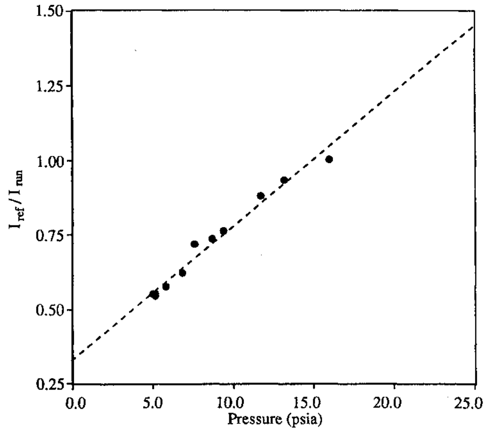

Fig. 4 Linear least-square fit of the calibration data.

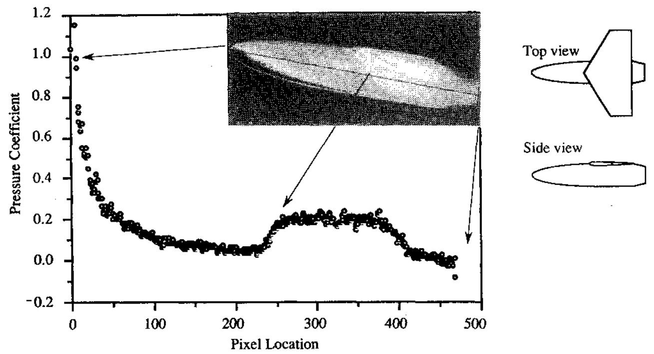

Fig. 5 Pressure distribution on a wing/body model at $M = 2.0$ and an 8 deg angle of attack measured using pressure sensitive paint (black and white rendering of color image).

$$\frac{I_{\mathrm{cal}}(T_{\mathrm{run}})}{I_{\mathrm{run}}} = m_{\mathrm{run}} P_{\mathrm{run}} + b_{\mathrm{run}} \tag{3}$$

The slope and intercept, m and b, are functions of temperature, and thus the subscripts indicate the temperature at which they are evaluated. In the case that P_{cal} is zero, $b = 1$ and $m = 0.21K_q$ (0.21 is the mole fraction of oxygen in air). Intensities at the calibration pressure are functions of temperature and are so indicated. Dividing Eqs. (2) and (3), and including the ratio of excitation intensities yields

$$P_{\mathrm{run}} = \left\{ (m_{\mathrm{ref}} P_{\mathrm{ref}} + b_{\mathrm{ref}}) \frac{I_{\mathrm{ref}}}{I_{\mathrm{run}}} \frac{I_{\mathrm{ex\text{-}run}}}{I_{\mathrm{ex\text{-}ref}}} \frac{I_{\mathrm{cal}}(T_{\mathrm{run}})}{I_{\mathrm{cal}}(T_{\mathrm{ref}})} - b_{\mathrm{run}} \right\} \frac{1}{m_{\mathrm{run}}} \tag{4}$$

This equation clearly shows that any temperature change in the paint between obtaining the reference image and the run image can affect the calculated pressure.

In the work presented here, temperatures were not measured accurately enough to make use of the variation of calibration coefficients with temperature. Instead, the ratio of coefficients at the two temperatures and the illumination intensity ratio were consolidated into two coefficients in the following equation:

$$P_{\mathrm{run}} = R \frac{I_{\mathrm{ref}}}{I_{\mathrm{run}}} + S \tag{5}$$

In a manner similar to Kavandi et al.,[3] wall tap pressures were used in a linear least-squares fit of this equation to determine R and S, which implies the assumption of an isothermal surface. A typical plot of this fit is shown in Fig. 4 for a test using the high-performance fighter model described later. The rms error between the data and the least-square fit is 8%. Much of this error is due to the change in luminescence caused by oil spots deposited on the paint during the wind-tunnel run.

All of the video images have an offset resulting from the CCD dark current and the noise levels associated with the camera system. Before dividing the intensities of the two images, the offset "dark" images, must be subtracted. A dark image is acquired by prohibiting any light from striking the CCD and then sampling an image. By subtracting this image from the run and reference images, the zero level is shifted such that zero incident light corresponds approximately (within the noise) to a zero grey level.

Having adjusted the zero, in the case of the digital camera, an attempt was made to account for differences in gain from each pixel across the CCD array. A calibration image was taken with uniform illumination across the CCD at a level near the top of its intensity range. By dividing the zero-corrected images by this image and multiplying them by its average, the effect of variable pixel gain was eliminated. This technique was applied to images from a test using a high-performance fighter model for which model movement was small and found to have a small effect on the overall pressure calculation. The pixel-to-pixel variation in gain is expected to influence the pressure calculations when model motion is large and the response of different pixels will be divided.

A major problem that occurs when using pressure sensitive paint, primarily in the case of sting-mounted models, is model movement. Typically the movement occurs when the flow is turned on, displacing the model from its location when the reference image was acquired. Thus, the two images cannot simply be divided pixel-by-pixel to obtain pressure. A transformation must be applied to realign the images. Several different approaches are currently being developed and tested for this transformation.

In the present work a simple shifting and stretching was performed on the run image to approximately fit it to the reference image. However, this method is only a preliminary attempt to solve the alignment problem. Since the model typically undergoes both a change in attitude and location relative to the camera, three-dimensional model geometry must be considered when transforming the run image back to the reference image. Work is currently underway to advance this method and will be reported in future papers.

VI. Results

The purpose of these tests was to demonstrate the method while gaining experience using the paint in a variety of flowfields and facilities. A great deal of information about the benefits, limitations, operational difficulties, and accuracy can be learned by examining these studies.

The paint, illuminator, and detectors were first demonstrated with a bench-top apparatus that used a small pressure vessel to test the response of the paint. One wall of the vessel was glass, allowing optical access for illumination and detection. The opposing wall was coated with a paint sample and the pressure in the vessel was varied with a regulator. The response of the paint at the different pressure levels was detected and evaluated. These levels corresponded to pressure levels expected for some of our wind-tunnel experiments. Promising results from this preliminary work justified implementing the paint system in a variety of aerodynamic applications.

A generic wing-body model, shown in Fig. 5, was used to test the paint over a wide range of Mach numbers. This test was conducted in a variable Mach number, 4 × 4 ft blow down wind tunnel at Mach numbers of 0.4, 1.4, and 2.0. The low-light video camera was used in conjunction with an 8-bit image processor to detect the paint response and to quantify the images. Model movement during the test prevented improvement of the signal that would result from averaging sequential images.

Surface pressures at $M = 2$ and 8-deg angle of attack are also shown in Fig. 5. The stagnation region at the nose of the model is clearly visible, and an extended high-pressure region is detected on the underside of the forebody. Another high-

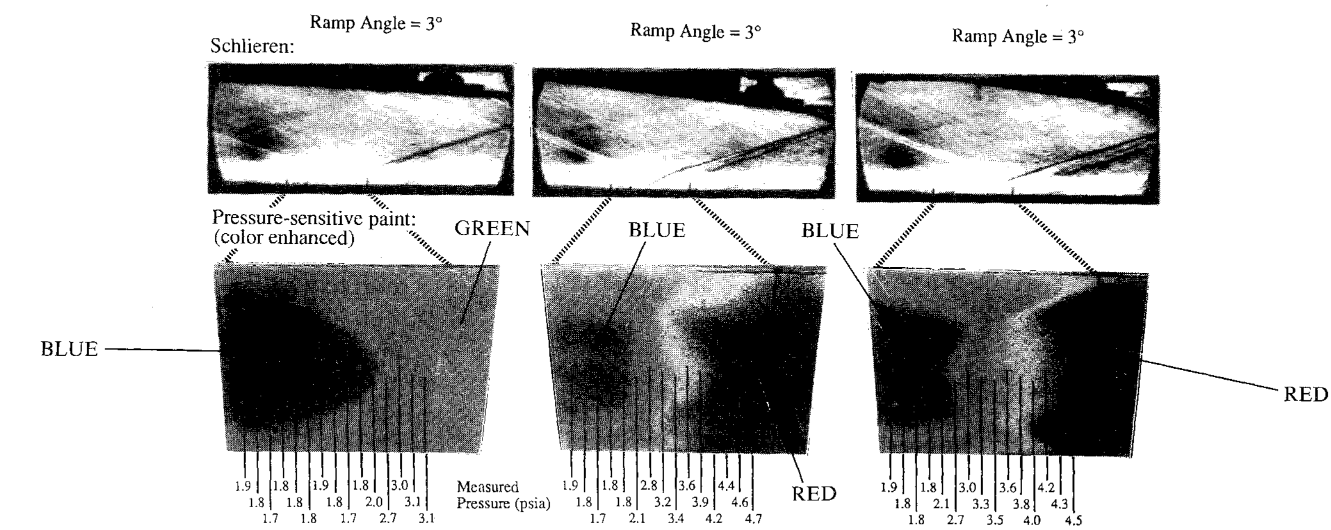

Fig. 6 Schlieren images and pressure distributions from shock/boundary layer interactions at $M = 3.5$ and three ramp angles using both pressure sensitive paint and wall taps. (The flow is from right-to-left; black and white rendering of color image.)

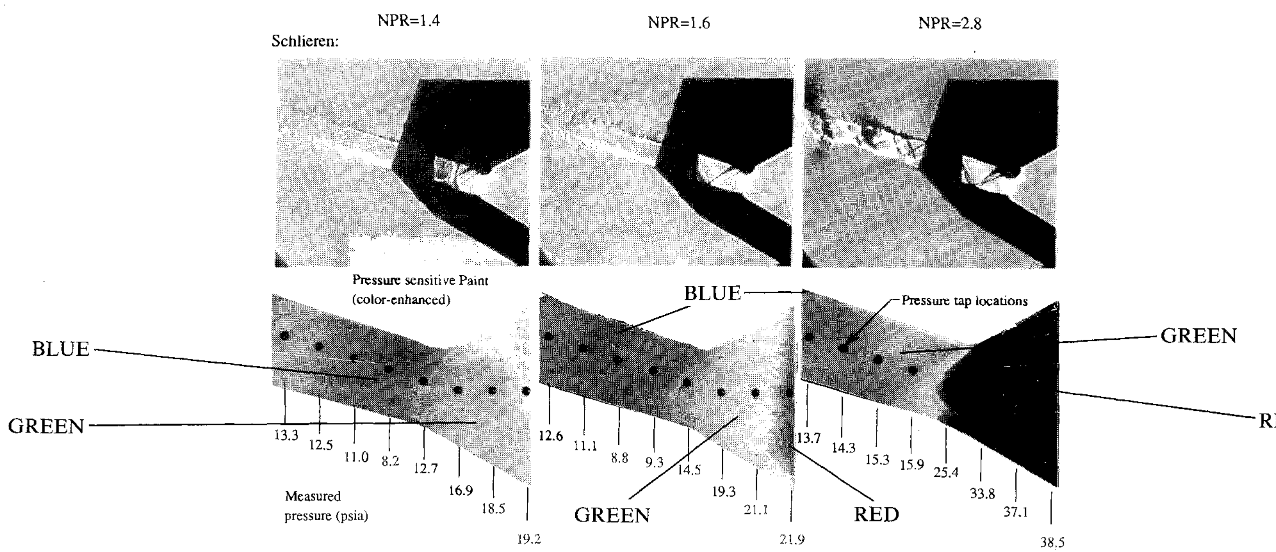

Fig. 7 Schlieren images and pressure distributions from a two-dimensional converging/diverging nozzle at three nozzle pressure ratios (NPR) using both pressure sensitive paint and wall taps. (The flow is from right-to-left; black and white rendering of color image.)

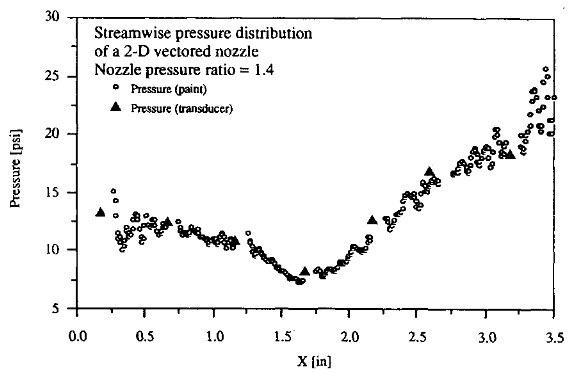

Fig. 8 Comparison of pressure measurements using the pressure sensitive paint technique and pressure transducers connected to wall taps.

pressure region is seen on the body under the wing where the wing shock intercepts the body. A row of luminescence data was sampled on the side of the model as shown in Fig. 5. This row of data was used to calculate the coefficient of pressure along the body. The model was originally designed for aerodynamic testing and was not equipped with pressure taps. Pressure information from the surface of this model was not available by conventional methods. The paint provided information (previously unattainable) about the pressure field on the model and demonstrates the utility of this measurement technique.

Several important lessons were learned while performing this test. First, the paint adhered to the model in the regions of highest wall shear stress, e.g., near the leading edges. Second, oil droplets deposited by the air flow onto the model surface affected the quenching process. Once painted, the model surface must be treated with care. Any contaminants on the surface appear as optical noise. Skin oils can fluoresce when excited and thereby introduce error to the pressure measurement at that location. Paint formulations currently under development at MDRL are less vulnerable to the effects of oil. Finally, these experiments demonstrated clearly the effect of model movement on the analysis of the images. The flow-on image must be mapped to the corresponding reference image for proper determination of the pressure distribution.

Pressure sensitive paint was also used to determine the pressure distribution below a shock-wave/turbulent-boundary layer interaction at Mach 3.5. A shock was generated using a full-span ramp and it impinged on the wind-tunnel floor. This test was conducted in a 1 × 1 ft blow down wind tunnel. The static pressure upstream of the interaction was 1.7 psia which caused a relatively high luminescence level. These high-light levels were easily detectable with the low-light video camera.

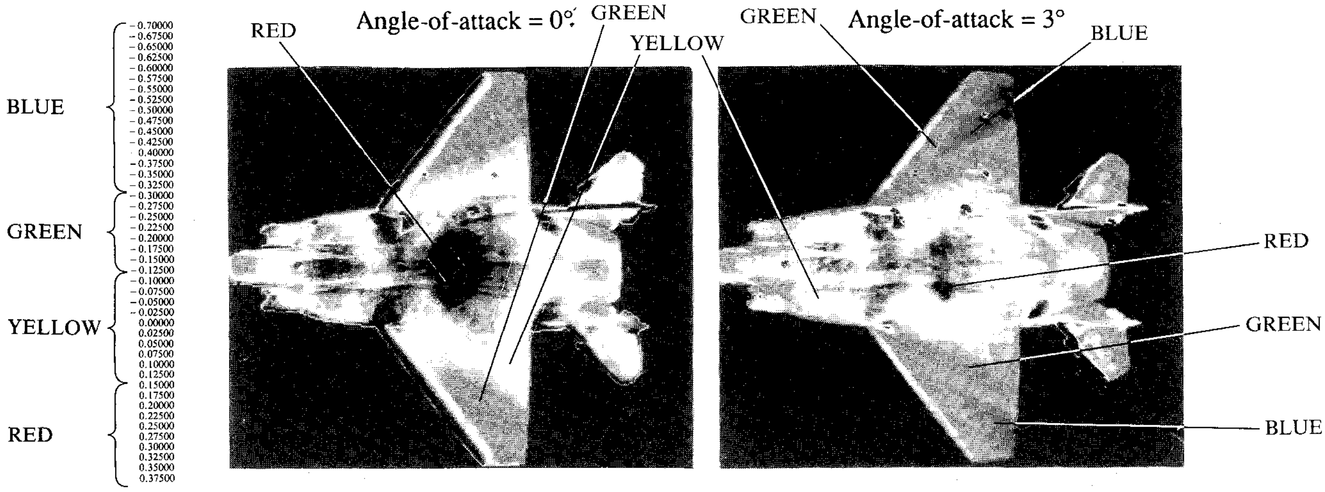

Fig. 9 Pressure distributions on a model of a high-performance fighter at $M = 1.2$ and 0 and 3 deg angle of attack measured with pressure sensitive paint (black and white rendering of color image).

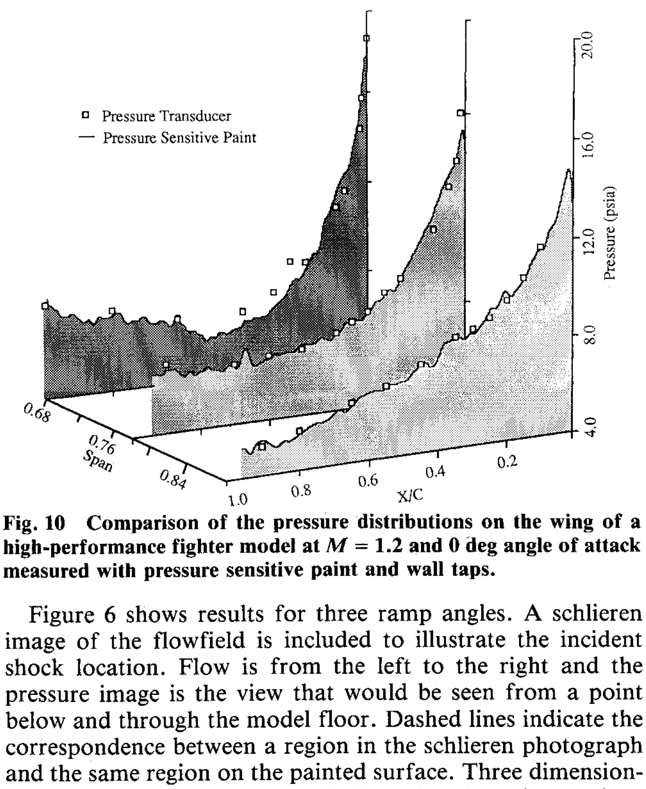

Fig. 10 Comparison of the pressure distributions on the wing of a high-performance fighter model at $M = 1.2$ and 0 deg angle of attack measured with pressure sensitive paint and wall taps.

Figure 6 shows results for three ramp angles. A schlieren image of the flowfield is included to illustrate the incident shock location. Flow is from the left to the right and the pressure image is the view that would be seen from a point below and through the model floor. Dashed lines indicate the correspondence between a region in the schlieren photograph and the same region on the painted surface. Three dimensionality caused by the skewed shock/boundary-layer interactions on the tunnel side walls is evident in the pressure distributions. Wall tap pressures are indicated for comparison; good correlation is seen between the paint response and pressure levels.

Pressure measurements were also made in a converging-diverging nozzle at three nozzle pressure ratios (NPR). Results from this experiment are shown in Fig. 7. The two-dimensional nozzle was equipped with two opposing windows for schlieren visualization (the right portion of the image). For the paint test, one window was replaced with a solid wall painted with pressure sensitive paint and instrumented with pressure taps. In this test, the paint response was also detected using the low-light video camera. There is a clear correspondence between the high-density gradient at the throat and the rapid color change. Pressures measured with wall taps and conventional pressure transducers are included for comparison. Colors corresponding to the measured pressures correlate well between these images.

A line of luminescence data was selected along the centerline row of pressure taps and these data were used to calculate pressures. Figure 8 shows a comparison of the pressures determined by the paint and those measured by the transducers. The calibration coefficients for the paint used in this comparison were obtained from an independent calibration using a pressure cell. Paint pressures were determined from a single video image with spatial averaging over a 3×3 pixel area. Scatter in the data at pressures higher than 25 psia reflects the low-light limit of the video camera, i.e. as the pressure increased, the luminescence decreased to a level that was too low for the camera to detect with precision. Overall agreement is approximately 10%, but the results could be improved by averaging several images to improve the signal-to-noise ratio.

Finally, pressure sensitive paint was used to measure the surface pressure on a high-performance fighter model at Mach 0.6, 0.9, and 1.2 and at angles of attack between −5 and 10 deg. This test was conducted in the 4×4 ft blow down facility. The model wing was instrumented with conventional pressure taps. Both the low-light video camera and the scientific-grade digital camera were used to detect the response. Results presented here were determined from the digital camera data; the video camera was primarily used for real-time monitoring of the luminescence. Pressure distributions on the model surface as determined from the pressure sensitive paint are shown in Fig. 9. Values of pressure coefficient are indicated with corresponding color coding. Pressure information is missing from several locations because contouring epoxy chipped away during the test, taking with it the pressure sensitive paint. In these locations no signal was detected. The influence of oil on the paint response is shown as streaks and several small dots visible in the yellow and red regions. Also visible in this image are three distinct dots on the right wing, which are fiducial marks. Distinct differences can be seen between the pressures at 0- and 3-deg angle of attack. Note the area of low pressure (blue) near the trailing edge at the wing tip which indicates a high loading. Because of the location and the limited number of the pressure taps on the wing, wing tip loading would be severely underestimated if only the tap measurements were available.

Samples of streamwise luminescence data from the wing were used to determine pressures for the data at 0 deg angle of attack. Several streamwise cuts through the wing are plotted in Fig. 10. Paint calibration coefficients were determined using a linear least-square fit to the wall tap pressures for each cut as discussed in Sec. V. Each point along the PSP curve represents a spatial average of a 2×3 pixel array from the image. In this case, each pixel corresponds to a square on the model surface with 0.0325-in. sides. Three of these pressure distributions are compared to those obtained from wall taps connected to electronically scanned pressure modules. Figure 10 shows good agreement between the two measurements and is encouraging. Pressure data with the spatial resolution provided by the paint technique could easily be used to determine aerodynamic loads.

VII. Summary

MDRL has developed a photoluminescent paint that is highly sensitive to pressure and is excited using visible light. A measurement system consisting of an illumination system, a detection system, and a data processing system was developed to utilize this paint for pressure measurements. Illumination was provided by a laser and fiber optic delivery system. The detection system was video based using both a low-light video camera and a digital camera with a scientific-grade CCD array. The utility of this paint system was demonstrated in four different flowfields covering a wide range of pressure levels and operating conditions. Several important factors were observed and must be considered in any pressure sensitive paint system. These include temperature effects, model movement, camera calibration, and interference from contaminants. Development of this paint system continues to address these factors and to extend the technique to new applications.

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